

The importance of discovering a 3:2 twin-peak QPO in a ULX

or how to solve the puzzle of intermediate mass black holes

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Abstract. Recently, twin-peak QPOs have been observed in a 3:2 ratio for three Galactic black-hole microquasars with frequencies that have been shown to scale as $1/M$, as expected for general relativistic motion near a black hole. It may be possible to extend this result to distinguish between the following two disparate models that have been proposed for the puzzling ultra-luminous X-ray sources (ULXs): (1) an intermediate-mass black hole ($M \sim 10^3 M_\odot$) radiating very near the Eddington limit and (2) a conventional black hole ($M \sim 10 M_\odot$) accreting at a highly super-Eddington rate with its emission beamed along the rotation axis. We suggest that it may be possible to distinguish between these models by detecting the counterpart of a Galactic twin-peak QPO in a ULX: the expected frequency for the intermediate-mass black hole model is only about 1 Hz, whereas, for the conventional black hole model the expected frequency would be the ~ 100 Hz value observed for the Galactic microquasars.

Key words. ULXs black holes – QPOs — X-ray variability – observations –

1. ULX: intermediate-mass black hole or Polish doughnut ?

The physical nature of the recently-discovered ultraluminous X-ray sources (ULXs) remains a puzzle. Several of these non-nuclear, pointlike X-ray sources have been discovered in nearby galaxies. They have apparent isotropic X-ray luminosities ten to hundred times greater than the Eddington limit for a $10 M_\odot$ black hole. The pointlike appearance of ULXs, together with their variability on timescales ranging from days to years, suggest that they must be compact accreting sources (Ptak & Griffiths 1999).

The high luminosities and compactness of ULXs were behind the claim that ULXs must be powered by accretion onto a new class of “intermediate-mass” black holes (Colbert & Mushotzky 1999; Makishima et al. 2000). In this interpretation, ULXs are $\sim 10^{2\pm0.5} M_\odot$ black holes radiating very near the Eddington limit. However, a different interpretation is also possible: a ULX could be powered by a highly super-Eddington accretion flow. From works of Paczyński and collaborators in the 1980s in Warsaw, it is known that thick accretion disks, which are supported by radiation pressure, are formed when the accretion rate is far above the Eddington value (Abramowicz, Jaroszyński & Sikora, 1978; Kozłowski, Abramowicz & Jaroszyński, 1978). Such a thick disk has a pair of very deep and narrow funnels along its accretion axis, which prompted Martin Rees to call this structure a “Polish doughnut.” The emergent radiation flux is beamed in the funnels and reaches values far in excess of the Eddington flux (Jaroszyński, Abramowicz & Paczyński, 1980; Abramowicz & Piran 1980; Sikora 1981; Madau, 1988). Thus, a ULX could very well be a Polish doughnut: i.e., an ordinary X-ray binary with a $\sim 10 M_\odot$ black hole that is accreting at a highly super-Eddington rate.

Both interpretations of ULXs, the intermediate-mass black hole and the Polish doughnut, face theoretical difficulties that have been discussed, for example, by Strohmayer & Mushotzky (2003) and by King et al. (2001). Rather than reviewing and attempting

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to elaborate the uncertain arguments used in these discussions, we point out instead an unambiguous and purely observational way to solve the ULX puzzle.

We suggest that the mass of a ULX could be unambiguously determined if a twin-peak QPO with frequencies in the ratio 3:2, $\nu_{\text{upp}}/\nu_{\text{lower}} = 1.5$, were to be discovered in the time variability of the ULX. Such twin-peak QPOs provide a precise mass estimate because of the scaling found by McClintock & Remillard (2003) in the twin-peak kHz QPOs in microquasars,

$$\nu_{\text{upp}} = 2.8 (M_{\odot}/M) \text{ kHz}. \quad (1)$$

The fit described by equation (1) is shown in the small insert to Fig. 1. For an extended discussion of the scaling see also Abramowicz & Kluźniak (2003); Kluźniak, Abramowicz, & Lee (2003); Abramowicz, Kluźniak, Stuchlík & Török (2004).

The key point of our suggestion is that with this calibration between mass and frequency in hand, Mirabel's well-known argument (e.g., Mirabel & Rodríguez, 1998) about the similarities in black hole accretion physics over the whole microquasar–quasar range may be used to fix the mass using the scaling provided by (1) and shown in Fig. 1.

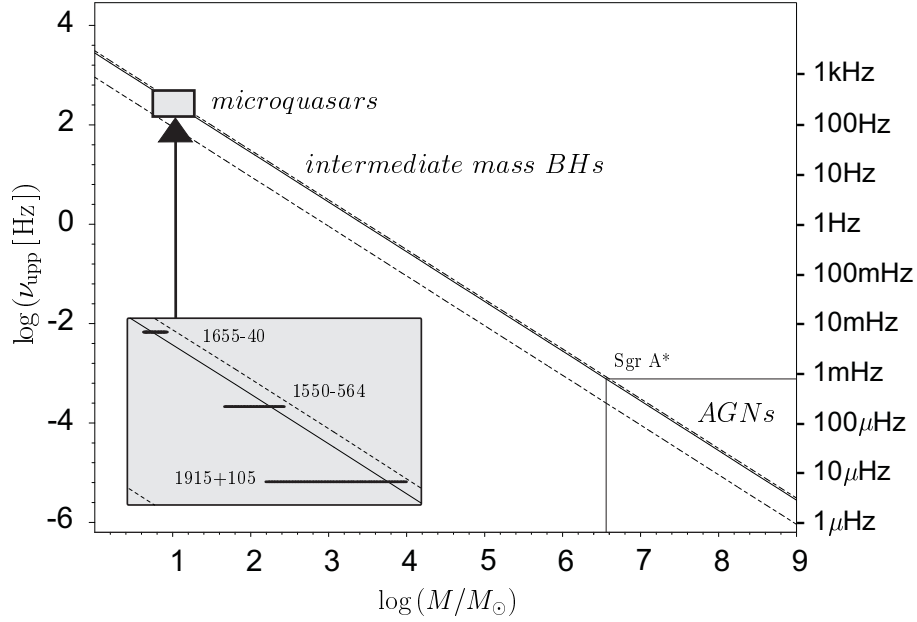


Fig. 1. Mirabel's microquasar-quasar analogy applied to the twin-peak QPOs with a 3:2 frequency ratio. The solid line is the frequency given by eq. [1], the dashed (upper) and dot-dashed lines are theoretical upper and lower limits to the upper of the twin frequencies corresponding to dimensionless black hole spin $a = 1$ and $a = -1$, respectively. One should note that the lack of *a priori* knowledge of black hole spin introduces relatively small errors in the mass estimate. The horizontal line marked Sgr A* corresponds to a prediction of what the upper frequency should be for the $3.6 \cdot 10^6 M_{\odot}$ black hole at the center of our Galaxy—this frequency coincides with that of the 17 minute flare (Genzel et al. 2003).

2. QPOs

We stress that not *all* of the high-frequency QPOs in microquasars (or neutron star sources) scale according to (1). Indeed, it is known that they do not. Thus, other (*non*-twin-peak) QPOs cannot be used to reliably estimate mass. This is why the remarkable discovery of a *single* QPO frequency in ULXs (Strohmayer & Mushotzky, 2003) is not conclusive in solving the ULX puzzle.

Many poorly understood quasi-periodicities have been observed in the radiation flux of low-mass X-ray binaries (van der Klis 2000). As shown by the variability of the frequencies in a class of sources, and even more clearly in individual sources, in general there is not a one-to-one correspondence between the observed frequency and the source mass. It is not difficult to understand why. In turbulent accretion disks around black holes, neutron stars, and white dwarfs most of the high frequency variability is likely connected with transient oscillatory phenomena that occur at various locations in the inner accretion disk.

Because these phenomena are not uniquely connected to any particular location that is fixed in relation to the gravitational radius, they do not scale with $1/M$. For example, the high-frequency QPOs vary within a few hours or days by several hundred Hz in individual neutron-star binaries. It is also clear that the QPOs in white dwarfs have frequencies orders of magnitude lower than the QPOs in neutron stars, although both classes of sources have a similar mass $M \approx 1 M_{\odot}$ (Mauche 2002; Warner et al. 2003). This must be related to the difference in the radii of white dwarfs and neutron stars. Similarly, the correlation of low and high QPO frequencies which spans two orders of magnitude for neutron star sources (Psaltis, Belloni & van der Klis

1999), cannot reflect a range of stellar masses, but rather indicates a range of radii (and hence Keplerian frequencies) where the QPOs are formed.

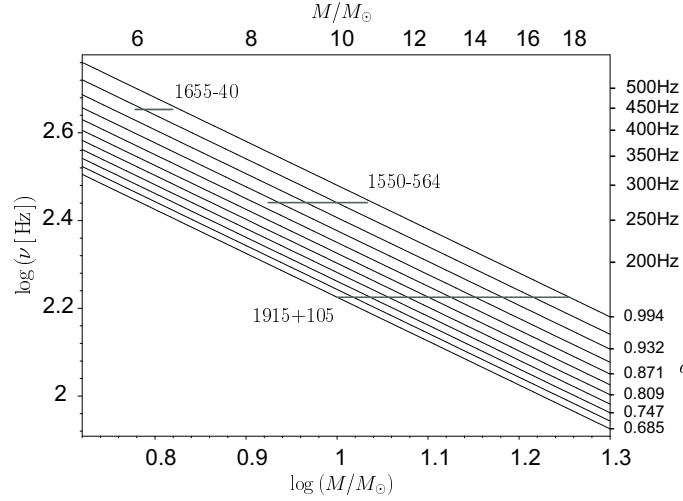


Fig. 2. The 3:2 parametric resonance model for kHz twin-peak QPOs in three microquasars. The observational data points from McClintock & Remillard (2003) are superimposed on the predictions of the parametric resonance model of black-hole accretion disk oscillations for various values of the spin parameter, a (lower values of a would give lower frequencies). The figure is from Abramowicz, Kluźniak, Stuchlík & Török (2003). The good agreement for reasonable values of the black hole spin shows that the empirical fit of eq. [1] may have a theoretical foundation, and that the spin of the black hole may be determined if the mass is known accurately.

3. The twin-peak QPOs in microquasars and the 3:2 resonance

The twin-peak QPOs in Galactic black holes are different. For three such microquasars, a pair of quasi-periodic oscillations (twin-peak QPOs) are observed that have fairly stable frequencies in a 3:2 ratio and rather high central values ($\sim 10^2$ Hz; McClintock & Remillard 2003).

Properties of these twin-peak kHz QPOs can be understood in terms of a non-linear resonance between the two epicyclic frequencies in the inner regions of the accretion disc (Kluźniak & Abramowicz 2000; Kluźniak & Abramowicz 2003 and references therein). In particular, the twin-peak 3:2 QPO frequencies correspond to a specific resonance radius that is fixed in terms of the gravitational radius of the central compact object. This is why these frequencies scale with $1/M$. Indeed, any general relativistic oscillation that occurs at an orbital radius fixed in terms of $r_G = GM/c^2$ must obviously scale with $\nu \sim [GM/(r_G)^3]^{1/2} \sim 1/M$. It appears that observations of the three microquasars that display twin-peak QPOs and have known masses confirm this scaling relation (Figs. 1,2; McClintock & Remillard 2003).

4. Conclusions

The detection of a twin-peak 3:2 QPO in a ULX would immediately determine its mass (see Fig. 1) and thereby solve the puzzle: is the correct model for a ULX based on an intermediate-mass black hole ($M \sim 10^3 M_\odot$) or a conventional black hole ($M \sim 10 M_\odot$) embedded in a Polish doughnut?

Finally, we note that Mirabel’s quasar-microquasar analogy suggests that one should also expect twin-peak QPOs with a 3:2 ratio in the microhertz range for quasars (Fig. 1; $M/M_\odot \sim 10^7$ to 10^9). In this connection, it is interesting to note that a 17 minute periodicity has recently been reported from the compact radio source Sgr A*, “a 3.6-million-solar-mass black hole” at the Galactic Centre (Genzel et al. 2003). This periodicity seems to correspond exactly to the 1 mHz frequency expected on the scaling discussed here (Fig. 1). However, the result is inconclusive because only a single oscillation frequency was observed. If the 17 minute flare period does indeed correspond to the upper (or lower) of the twin-peak QPOs in microquasars, it would be interesting to see whether a 26 minute (or 12 minute) quasi-periodicity may also be present in the source.

After this paper was completed, Aschenbach et al. (astro-ph/0401589) reported X-ray QPOs from Sgr A*. The claimed periods include 1150 s (19 minutes) and 700s (12 minutes).

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References

- Abramowicz M.A., Jaroszyński M., Sikora M. 1978, A&A 63, 221
- Abramowicz M.A. & Kluźniak W. 2003, in X-Ray Timing 2003: Rossi and Beyond, P. Kaaret, J. Swank, eds. in press, astro-ph/0312396
- Abramowicz M.A., Kluźniak W., Stuchlík & Török 2004, submitted, astro-ph/0401464
- Abramowicz M.A., Piran T. 1980, ApJLett. 241, L7
- Colbert, E. J. M., Mushotzky, R. F. 1999, ApJ 519, 89
- Genzel, R., Schoedel, R., Ott, T., Eckart, A., Alexander, T., Lacombe, F., Rouan, D., Aschenbach B. 2003, Nature 425, 934
- Jaroszyński M., Abramowicz M.A., Paczyński B. 1980, Acta Astronomica 30, 1
- King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., Elvis, M. 2001, ApJ 552, L109
- Kluźniak W., Abramowicz M.A. 2000, Phys. Rev. Lett. (submitted), astro-ph/0105057
- Kluźniak W., Abramowicz M.A. 2003, 12th Workshop on General Relativity and Gravitation, (Tokyo: Tokyo University Press), astro-ph/0304345
- Kluźniak W., Abramowicz M.A., Lee, W.H. 2003, in X-Ray Timing 2003: Rossi and Beyond, P. Kaaret, J. Swank, eds., in press
- Kozłowski M., Jaroszyński M., Abramowicz M.A. 1978, A&A 63 209
- Mauche, C. 2002, ApJ 580, 423
- Madau, P. 1988, ApJ 327, 116
- Makishima, K., et al. 2000, ApJ 535, 632
- McClintock J.E, Remillard R.A. 2003, astro-ph/0306213 v.2
- Mirabel I.F, and Rodríguez L.F. 1998, Nature 392, 673
- Psaltis D., Belloni T., van der Klis M. 1999, ApJ 520, 262
- Ptak, A., Griffiths, R. 1999, ApJ 517, L85
- Sikora M., 1981, MNRAS 196, 257
- Strohmayer T.E., Mushotzky R.F. 2003, ApJLett. 586, L61
- van der Klis M. 2000, Ann. Rev. of A&A 38, 717
- Warner, B., Woudt, P.A., Pretorius, M.L. 2003, MNRAS 344, 1193